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Performance of a fertiliser management algorithm to balance yield and nitrogen losses in dairy systems

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ABSTRACT

To demonstrate the use of a previously developed fertilisation algorithm and to determine its potential effects on nitrogen (N) losses from grazed pastoral systems, a simulation study was performed using the Agricultural Production Systems Simulator (APSIM). The study considered a dairy system with irrigated ryegrass pasture on a silt loam soil in the Canterbury region of New Zealand. Firstly, the algorithm was parameterised for each month based on pasture yield and N contents from simulation run over 20 years using a wide range of N fertilisation rates. The algorithm was then used in the simulation of fertilisation management of a hypothetical dairy farm under different scenarios where its performance for increasing pasture yield with more efficient N use was tested. The scenarios were based on different yield targets for the proposed algorithm (50, 75, 90 or 100% of the average maximum yield) and included scheduled fertilisation to mimic more typical management. For more realistic evaluation, the simulations took into account changes in stocking rates and N flows in the farm resulting from the different fertiliser management. The simulations also considered the uneven return of urinary N by grazing animals, which are crucial to determine N losses in these systems.

Both pasture yield and N losses were in general agreement with available measured data from similar systems and with comparable N inputs. Thus providing support for the simulation study as a valid way to demonstrate the potential effects of changing fertiliser management. The average of simulations run over 10 years showed that direct losses from the fertiliser were lower when the fertilisation was controlled by the proposed algorithm compared with scheduled fertilisation at similar N rates. However, with animals in the paddock and thus including the effects of urine patches, N losses were not significantly different. As there was an increase in pasture yield and consequent stocking numbers, the area receiving urinary N increased, counter balancing the increased N use efficiency when using the algorithm. Nonetheless, the larger yield lead to greater farm productivity, and this resulted in about 13% reduction in N losses per unit of milk production.

1. Introduction

The worldwide intensification of agriculture over the last century has led to a significant increase in crop and pasture production. A major driver for this intensification was the use of nitrogen (N) fertilisation, leading to higher plant growth and consequently greater stocking rates in pastoral systems. The increasing level of intensification has been linked to adverse effects on the environment including eutrophication of surface waters, elevated nitrate levels in ground water, and increased emissions of both nitrous oxide and ammonia (Monaghan et al., 2007b; Saggar et al., 2011; Bos et al., 2013). In New Zealand, pastures typically consist of grass/legume mixtures, generally perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.), with the later providing a considerable part of the N input via N fixation (Ledgard et al., 2001, 2009). However, dairy systems are increasingly reliant on N fertiliser, with typical rates varying between 100 and 200 kg N/ha per annum (Clark et al., 2007; MPI, 2012; Chapman et al., 2017), but annual rates of up to 400 kg N/ha can be occasionally used in more intensive irrigated systems.

While direct N losses from fertilisers applied to grazed pastures are generally low, in years with low pasture growth and/or high rainfall events, substantial N leaching can occur (Barton et al., 2009; Vogeler and Cichota, 2016). However, extensive research has shown that the main source for N losses in these systems is the urine deposited by

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grazing animals (Ball and Ryden, 1984; Ledgard et al., 1999; Di and Cameron, 2002; Decau et al., 2004; Pakrou and Dillon, 2004). In this context, fertiliser inputs can increase N leaching indirectly by providing more forage, enabling higher stocking rates, higher N intake, and consequently more N excretion. A potential option for reducing nitrate leaching and minimising risk of surface and groundwater pollution is by matching fertilisation N rates and timing to pasture needs (Ledgard et al., 1988; Monaghan et al., 2007a). A series of recommendations and good management practices have been developed over time and N budgeting tools are available to aid on strategic nutrient management (Wheeler et al., 2003; Brown et al., 2005; Monaghan and de Klein, 2014), however resources for helping on tactical management still require development and validation. Two promising technologies that can fill this gap, modelling and sensors, have already been implemented for some cropping systems (e.g. Li et al., 2007; Bragagnolo et al., 2013; Diacono et al., 2013), but the use of these technologies is still incipient in pastoral systems and needs validation. Measurements of N in the soil or plants can be costly and too slow for tactical management, whereas the use of a plant growth model in conjunction with sensor technology can be fast, site specific, and cost effective (Muñoz-Huerta et al., 2013; Roberts et al., 2015). Fertiliser recommendations based on this combination could increase the nitrogen use efficiency of dairy pastures by providing fine-tuned estimates of N requirements based on current plant N status and the potential growth over the near future.

A simple algorithm for determining N fertilisation rate to achieve a target percentage of the maximum average yield based on plant N status was presented by Vogeler and Cichota (2017). Such tool could easily be coupled with remote sensing to improve fertiliser management in pastoral farms, although the methodology still needs some development and field validation. The simulation study presented here goes some way to complement that work, with the specific objectives of (i) estimating the month-specific parameters for the multi-variate model developed by Vogeler and Cichota (2017), (ii) testing the use of the algorithm for estimating fertilisation rates for different yield targets, (iii) evaluating the model performance regarding pasture yield and N losses, including direct N leaching from fertiliser and indirect losses from urine patches, as well as denitrification and volatilisation, and (iv) assessing the likely differences in production and N losses when using the algorithm compared to the use of typical fertilisation rates.

2. Material and methods

The simulation study was done using the APSIM model and for a pastoral system mimicking a dairy farm in the Canterbury region of New Zealand. The runs for obtaining data to parameterise the fertilisation algorithm used rather artificial combination of fertiliser rates and aimed to capture short term N responses and its correlation with environmental conditions. The runs for testing the algorithm were made independently of those used for parameterisation, they considered more realistic farming conditions and run over different years to reduce potential bias.

2.1. APSIM model and base simulation setup

The simulations were performed using the APSIM modelling framework, version 7.7 (Keating et al., 2003; Holzworth et al., 2014). APSIM is a modular process-based modelling framework maintained by the APSIM Initiative (www.apsim.info) with an extensive record for simulating plant growth and how it is affected by management and environmental conditions (a comprehensive list of references is available in their website). The primary modules used in the simulations for this study included SWIM2 (Huth et al., 1996; Verburg et al., 1996), which uses numerical solutions of the Richards' equation for describing water flow and the convection-dispersion equation for solute transport; the SurfaceOM and SoilN modules (Probert et al., 1998) for soil C and N transformations; and the AgPasture module (Li et al., 2011), modified to account for remobilisation of N from maturing tissue (Vogeler and Cichota, 2016), for describing pasture growth and N uptake. A series of manager scripts (Moore et al., 2014) were used to describe the pasture management, including defoliation with associated urine depositions and residue returns, as well as the application of irrigation and fertiliser according to rules described below.

Table 1

Selected basic soil properties for the Templeton Soil Loam used in the simulations. Where: ρ_B is the soil bulk density, θ_S is the saturated water content, θ_{FC} and θ_{WP} are the water content at -10 and -1500 kPa, k_S is hydraulic conductivity at saturation and OC is organic carbon content.

Layer (mm)	ρ_B (Mg/m^3)	θ_S (m^3/m^3)	$\theta_{0.1}$ (m^3/m^3)	θ_{15} (m^3/m^3)	k_S (mm/h)	OC (%)
0–150	1.35	88.0	0.44	0.36	0.18	3.1
150–350	1.42	20.0	0.43	0.32	0.17	1.4
350–550	1.37	18.0	0.44	0.32	0.10	0.4
550–900	1.41	103.0	0.43	0.27	0.10	0.3
900–1000	1.50	41.0	0.40	0.31	0.17	0.2
1000–1500	1.42	82.0	0.42	0.35	0.11	0.2

The soil for all simulations was based on a Templeton silt loam (Typic Immature Pallic; Hewitt, 2010), similar to that described in Snow and White (2013). This is a medium-to-heavy textured soil with approximately 135 mm of plant available water in the top 75 cm and it was assumed that the field was under long-term continuous pastoral use; basic parameters are given in Table 1. Daily weather data for Lincoln, NZ (−43.625S, 172.475E) was obtained from the Broadfield weather station (cliflo.niwa.co.nz).

The pasture simulated contained ryegrass only and the pasture model used the modifications and the same setup as described in Vogeler and Cichota (2016). The basic management consisted of harvesting the pasture to a residual of 1500 kg/ha dry matter (DM) on the 15th day of each month. A uniform return of dung, at a rate of 300 kg DM/ha with 1.6% N content, was simulated after each grazing. Although both dung and urine are typically deposited to a small fraction of the paddock area, the impact of dung on N cycling is quite limited and so only a uniform return was considered here. The amount returned represents average return of biomass and N over a typical 10 year simulation period and did not vary for the different fertilisation regimes. For urinary N, a uniform return at a rate of 10 kg/ha was used for those simulation where explicit return of urine was not considered (see description of specific simulations below). In New Zealand pasture-based dairy farms employ an intensively managed rotational grazing system throughout the year. Under this rotational grazing, N excreta return is patchy and covers only about 2–5% of the paddock area during a grazing event (Pleasants et al., 2007; Snow et al., 2009). To simulate this situation, simulations were run in parallel with and without urinary N depositions and the outputs were aggregated based on the relative areas (details are given below). Irrigation was enabled from October to April simulating a centre-pivot system with a minimum return period of 24 h. Irrigation was applied at a rate of 10 mm/day whenever the soil water deficit (SWD) in the upper 300 mm soil profile was below 30 mm, and stopped when the SWD was 5 mm or less. The fertiliser whenever used was urea and was applied after the harvests, the N rate varied according to the simulation run, as described below.

To demonstrate its feasibility, this base simulation setup was tested against reference pasture production data (www.dairynz.co.nz/ feed/ pasture-management/pasture-growth-data). The data originated from an irrigated dairy farm near Lincoln, NZ; the soil was a light sandy loam, fertilised, and the pasture consisted of a ryegrass-white clover mixture.

2.2. Fertiliser algorithm parameterisation

The multi-variate model developed previously by Vogeler and